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BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

SUBJECT: 4B Experiment Pointing Capabilities of the WACS - Case 620

DATE: April 10, 1969

FROM: J. J. Fearnsides

[redacted]

ABSTRACT

This memorandum presents the results of a study to determine the compatibility of the 4B Experiment List with the capabilities of the WACS. It was determined that:

1. The entire set of experiments which require pointing can be done for approximately 40.6 pounds of propellant This represents only 5% of the WACS impulse capacity.

2. All experiments, including T025 and S020, can be made compatible with the pointing accuracy capability of the WACS.

(NASA-CR-106875) FOUR B EXPERIMENT POINTING CAPABILITIES OF THE WACS (Bellcomm, Inc.) 28 p

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MEMORANDUM FOR FILE

INTRODUCTION

The results of a study to determine the compatibility of the 4B Experiment List(13)* with the capabilities of the Workshop Attitude Control System (WACS) are presented. This compatibility was investigated without invoking the added capabilities of a flexible scientific airlock(9) or the S019 mirror system. The T027 boom was considered because, unlike the flexible airlock and the mirror system, it is in an advanced stage of development.

CONCLUSIONS

The principal results are:

1. The entire set of experiments requiring pointing can be done for approximately 40.6 pounds of propellant which implies 10,844 pound-seconds of total impulse. This represents only 5% of the entire WACS propellant capability.**

2. All experiments, including T025 and S020, are compatible with the pointing accuracy capability of the WACS. The compatibility of T025 is established by noting that the discs of the coronagraph overoccult the sun.*** With regard to S020, work done at MSFC(6) indicates that the limited manual control capability already baselined(8) in the WACS is sufficiently accurate.

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* Superscripted numbers in parentheses indicate references listed at the end of the report.

** MSFC has questioned whether there is enough WACS propellant to afford even 40.6 pounds. The author expects, however, that further study of the WACS impulse budget will reveal that this amount of propellant can be allotted to the experiments.

*** Experiment requirements are presented in detail in a Bellcomm Memorandum for File, "Experiment Pointing Requirements for AAP 1/2 and AAP-3A Missions," T. C. Tweedie, Jr., April 10, 1969, which is a companion to this memorandum.

The conclusion is that there are ways of pointing these experiments in an economical manner that are consistent with both the experiment requirements and WACS capabilities. Moreover, it can be done without the design and development of a flexible airlock or the S019 mirror system.

WACS-EXPERIMENT COMPATIBILITY REVIEW

TECHNOLOGY

T027 - ATM Contamination Measurement

Nominal Spacecraft Attitude During Experiment - X-POP.

Possible Accuracy Incompatibilities - WACS control with a 1/2 degree deadband is adequate.

Necessary OA Maneuvers - None required for $|\beta|<40°$* because of a 2 degree of freedom platform mounted on an extended boom.

Propellant Requirement - None for $|\beta|<40°$.

Comments - $|\beta|<40°$ for 290 days per year.

T025 - Coronagraph Contamination Measurements

Nominal Spacecraft Attitude During Experiment - X-POP.

Possible Accuracy Incompatibilities - It has been shown[2] that the accuracy requirement of $\pm$ 1/2° is incompatible with a WACS deadband of 1/2°. However, this requirement is seen to be unnecessarily stringent when the overocculation mentioned in Reference 1 is considered. The experiment is considered compatible with the WACS pointing capability under these conditions.

Necessary OA Maneuvers - Vehicle must be pitched through an angle equal to β.

Propellant Requirement -

1) Maneuvers - It is shown in Appendix A that a pitch maneuver at 0.1 degrees per second requires approximately 246 pound-seconds of impulse. Two maneuvers per orbit over 4 orbits yields an impulse of 1968 pound-seconds.

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* β is the angle between the solar vector and the orbital plane.

2) Holding Off-Nominal Attitude - A conservative estimate for the impulse required to maintain the nominal X-POP attitude is 100 pound-seconds per orbit.(3) Figure 1, Appendix B shows that 160 pound-seconds per orbit is required to hold the vehicle at 5 degrees off-nominal and 225 pound-seconds per orbit is required to hold the vehicle at 10 degrees off-nominal. Assuming that the off-nominal attitude must be held for a half orbit, the increase in propellant consumption is approximately

   a) 30 pound-seconds per orbit for 5 degrees
   b) 62.5 pound-seconds per orbit for 10 degrees.

   The total impulse for operation of T025 is, then, 2088 pound-seconds worst case for $|\beta|<5°$ and 2218 pound-seconds worst case for $|\beta|<10°$. This represents propellant consumptions of 7.8 pounds and 8.3 pounds, respectively.

Comments - Limiting $|\beta|$ to 10° imposes a mild performance contingency on this experiment. The launch times and launch dates for which the minimum value of β which can be achieved is greater than 10° are represented by the points inside the smaller "eyes" in Figure 3, Appendix B.

EARTH RESOURCES

S101 - Multispectral Terrain Photography

Nominal Spacecraft Attitude During Experiment - X-POP, Z-LV.

Possible Accuracy Incompatibilities - ± 10° accuracy, within WACS capability.

Necessary OA Maneuvers - Vehicle must make 15 passes over the earth in X-POP, Z-LV mode. For purposes of calculating propellant requirements, it will be assumed that the local vertical mode must be acquired from X-POP 5 times and held for 3 orbits at a time.

Propellant Requirements

a) Acquire X-POP, Z-LV from X-POP - For an orbital altitude of 210 nm, the orbital rate is approximately .065 degrees per second. This will require 65% of the propellant calculated for the roll maneuver in Appendix A or approximately 25 pound-seconds.

b) Hold X-POP, Z-LV - Based on results from Reference 3, the impulse required to maintain the X-POP, Z-LV orientation is 75 pound-seconds per orbit. This is lower than that required to maintain X-POP because of the reduced gravity-gradient torque on the roll axis.

c) Reacquire X-POP - Since this is just the reverse of the procedure in paragraph a), the impulse requirement is also 25 pound-seconds.

The total maneuvering impulse is 250 pound-seconds for 5 mode changes but there is a total of 375 pound-seconds saved by flying 15 orbits in the X-POP, Z-LV mode. This experiment therefore impacts the solar panel power supply rather than the WACS.

Comments - It is assumed that ground communication can inform the spacecraft in advance of favorable cloud cover conditions.

SCIENCE

S019 UV Stellar Astronomy

Nominal Spacecraft Attitude During Experiment - X-POP; X-POP, Z-LV.

Possible Accuracy Incompatibilities - $\pm$ 2° can be met by the WACS.

Necessary OA Maneuvers - The principal investigator[(4)] indicates that this experiment is compatible with the WACS by use of only roll maneuvers.* Thus the following "typical" orbit is considered.

1) Acquire X-POP, Z-LV at orbital noon. This is an economical way of getting the scientific airlock pointed away from the earth during the dark portion of the orbit.

2) Point the scientific airlock to some target in the orbital plane. Since the roll rate is already .065 degrees per second relative to an inertial coordinate system which is referenced to the orbit plane, a

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* See also Reference 1.

.1 degrees per second maneuver in the same direction to an inertial target only requires an increase of .035 degrees per second. Of course, a change in roll rate of -.1 degrees per second will be required to stop the spacecraft. It should never have to be required to maneuver in a direction opposite to the orbital rate.

3) Establish specified "smearing" rates - The body rate about the axis parallel to the dispersion of the prism must be between .0028 degrees per second and .011 degrees per second and all other rates should be less than .0028 degrees per second. One way of achieving these rates at a moderate propellant cost is to align the dispersion of the prism with the roll axis[1] and note that the specified rates are compatible with the uncontrolled roll motion over small angles. In addition, the nominal X-POP control law will keep the pitch and yaw rates well below the roll rates. Tables 1 through 4 illustrate the attitude (ψ) and the rate (ω) about the roll axis starting from rest and with the pitch axis making various angles with the local vertical. The general conclusion is that the natural motion of the spacecraft will provide the required body rates for periods which exceed the longest exposure (120 seconds). If the spacecraft roll rate is then reversed the attitude will drift back towards the original starting point through approximately the same rates.[5] This means that another long exposure or two shorter exposures can be done on the return maneuver. Further, since the spacecraft is moving against the disturbing torque the rate is also being diminished.

4) Reacquire X-POP.

Propellant Requirement -

1) Acquire X-POP, Z-LV at orbital noon 27 times. This assumes that only one star field per orbit can be photographed and, therefore, represents the worst case. Working from the roll axis maneuvering calculation in Appendix A,

$$\text{Impulse} = (27)(.65)(38.72) \doteq 680 \text{ pound-seconds.}$$

2) Stellar Pointing -

a) Provide a $\Delta\omega$ of .035 deg/sec 27 times

Impulse = (27)(.35)(38.72) ≃ 366 pound-seconds.

b) Provide a negative $\Delta\omega$ of .1 deg/sec to stop the vehicle 27 times.

Impulse = (27)(38.72) ≃ 1,046 pound-seconds.

3) Reverse "Natural" Motion - Assuming a maximum ω of .012 deg/sec, the reversal requires a $\Delta\omega$ of .024 deg/sec. This is done twice per star field for 27 star fields.

Impulse = (27)(2)(.24)(38.72) ≃ 502 pound-seconds.

4) Reacquire X-POP - 2092 pound-seconds

Total Experiment Impulse ≃ 4,686 pound-seconds

Total Experiment Propellant Consumption ≃ 17.4 pounds.

Comments - If two star fields per orbit are photographed, only 14 acquisitions of X-POP, Z-LV are required. Further propellant savings can be realized if part of the experiment is conducted in successive orbits.

S018 - Micrometeorite Collection

This experiment will probably(1) be flown as S149 which requires no pointing. If not, an X-POP, Z-LV orientation with thrustor firings is a relatively inexpensive alternative.

S073 - Gegenschein - Zodiacal Light

Nominal Spacecraft Attitude During Experiment - X-POP for daylight pass, X-POP, Z-LV for nighttime passes.

Possible Accuracy Incompatibilities - None.

Necessary OA Maneuvers - The nighttime portion of experiment is conducted in three consecutive orbits. The sequence is then, acquire X-POP, Z-LV, hold for 3 orbits, reacquire X-POP. The daytime portion is compatible with X-POP.

Propellant Requirement - The 50 pound-second impulse used for acquisition and reacquisition is more than offset by the 75 pound-second impulse saved flying X-POP, Z-LV, rather than X-POP.

Comments - Uses T027 boom. No propellant required.

S020 X-Ray/UV Solar Photography

Nominal Spacecraft Attitude During Experiment - X-POP.

Possible Accuracy Incompatibilities - It has been shown(2) that with a .25 degree deadband the WACS pointing accuracy is .43 degrees. This is incompatible with the specified .25 degree accuracy. The alternatives are a smaller deadband, say .125 degrees, or a manual controller. The latter has been shown(6) to be able to hold the spacecraft within .1 degree in both roll and pitch for periods up to a half orbit without tiring the operator. There is no control strategy that can maintain this accuracy passively, without use of the WACS.

Necessary OA Maneuvers - The vehicle must be pitched through an angle equal to β to point the spectrometer at the sun.

Propellant Requirement - Assume $|\beta|$ = 15 deg. The maneuvers and orientations requiring an increase in WACS propellant over the nominal X-POP mode are:

1) Maneuver the spacecraft through an angle equal to 15° at a rate of 0.1 deg/sec. Stop the spacecraft when spectrometer is pointed at the sun. From Appendix I, a pitch maneuver requires a total impulse of approximately 246 pound-seconds. The EIRD for S020 estimates the duration of the experiment is the daylight portion of 6 orbits. Thus, the total impulse for this maneuver is 1476 pound-seconds.

2) Hold the spacecraft 15 degrees off nominal for 45 minutes. This is done in one of two ways.

   a) Automatic Control - This method would use the WACS with a .125 degree deadband. According to Figure 2(7), Appendix B, the .125 degree deadband case uses approximately 1.3 times the propellant used by the 0.5 degree case. Since 100 pound-seconds has been used for the latter, it is estimated that 130 pound-seconds per orbit would be required to hold X-POP within the smaller deadband. Figure 1 Appendix B shows that a 15 degree off-nominal hold requires 3.3 times the nominal X-POP. If this is done for 6 half-orbits the total increase in the WACS impulse requirement is

$$6\left[(3.3)\left(\frac{130}{2}\right) - \frac{100}{2}\right] = 987 \text{ pound-seconds.}$$

b) Manual Control - Case 13, Reference 6 shows that 15 degrees off-nominal can be held for a half orbit at an expense of 200 pound-seconds of impulse. This is an increase of 150 pound-seconds per half orbit which yields a total impulse requirement of 900 pound-seconds.

3) Reacquire X-POP - 1476 pound-seconds

Total Impulse Requirement with Automatic Controller

$\simeq$ 3940 pound-seconds.

Propellant Consumption $\simeq$ 14.9 pounds.

Comments - The "manual" controller is merely manual operation of the attitude bias function already baselined for the WACS.(8) In addition, the manual controller provides better accuracy, fewer thrustor firings and a smaller average error. $|\beta|$ = 15 degrees was used because this was the data available on the manual controller. The propellant consumption would obviously be less if $|\beta|$ = 5 degrees or $|\beta|$ = 10 degrees were used as in T025.

S009 - Nuclear Emulsion

This experiment is compatible with the WACS and is operated in the gravity-gradient orientation between manned missions.

S063 - UV Airglow Horizon Photography

Nominal Spacecraft Attitude During Experiment - X-POP for nighttime passes, X-POP, Z-LV for daytime passes.

Possible Accuracy Incompatibilities - None.

Necessary OA Maneuvers - One orbit of X-POP, Z-LV orientation is estimated for the Daytime Earth Photography portion of the experiment. Since this is merely a hand-held camera, it is expected that it can be accomplished on one of the Z-LV orbits associated with S019.

J. J. Fearnsides

1022-JJF-ep J. J. Fearnsides

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4. Henize, Karl G., "Compatibility of Experiment S019 With the Proposed Attitude Control of the AAP Cluster," July 11, 1968.

5. Personal communication with J. Kranton.

6. Rupp, C. C., "Manual Control of the WACS," MSFC No. R-ASTR-NG-154-68, December 13, 1968.

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11. Culbertson, P. E., "Cluster Attitude Control for Experiment Pointing," Memorandum, January 23, 1969.

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APPENDIX A

PROPELLANT REQUIREMENT FOR MANEUVERS

A approximate expression for the propellant consumed in a spacecraft maneuver is presented below. The equations of motion expressed in vector notation are

(A-1) $$\underline{I\dot{\omega}} + \underline{\omega} \times I\underline{\omega} = \underline{T}_c + \underline{T}_d$$

where
I = inertia tensor
$\underline{\omega}$ = body rate
$\underline{\dot{\omega}}$ = time derivative of $\underline{\omega}$
$\underline{T}_c$ = control torque
$\underline{T}_d$ = disturbing torque.

For small motion about an inertial attitude,

(A-2) $$\underline{\omega} \times I\underline{\omega} \simeq 0.$$

If $\underline{T}_c >> \underline{T}_d$, equation (A-1) can be rewritten as

(A-3) $$I_k\dot{\omega}_k \simeq T_{ck}, \qquad k = x, y, z.$$

Assuming T_{ck} is constant over the firing interval, the change in angular momentum associated with a thrustor ignition is

(A-4) $$\Delta H_k = I_k(\omega_{k2} - \omega_{k1}) = T_{ck}(t_2 - t_1)$$

where t_1 = beginning of firing interval

t_2 = end of firing interval

ω_{k1} = angular rate of S/C about k^{th} axis at t_1

ω_{k2} = angular rate of S/C about k^{th} axis at t_2

If a maneuvering rate of .1 degree/second is desired, then

(A-5) $$\omega_{k2} - \omega_{k1} = .1 \text{ deg/sec.} = 1.745 \times 10^{-3} \text{ rad/sec.}$$

and

(A-6) $$(t_2 - t_1) = t_{on} = 1.745 \times 10^{-3} \frac{I_k}{T_{ck}} \text{ sec.}$$

ROLL AXIS MANEUVERS

Single Engine Thrust - 22 pounds

Number of Engine Fired - 2

Moment Arm - 11.25 feet

T_{cx} = (44)(11.25) = 495 foot-pounds

I_x = 0.250211×10^6 slug-feet^2

t_{on} = 0.88 seconds

Impulse = (44)(0.88) ≐ 38.72 pound-seconds

Propellant = 0.14 pounds with an I_{sp}* = 270 seconds

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*The steady-state value of I_{sp} is used for maneuvers because they involve long pulsing intervals. For attitude hold propellant calculations the I_{sp} is taken to be 250, the minimum impulse bit value.

PITCH AXIS MANEUVERS

Single Engine Thrust - 22 pounds

Number of Engines Fired - 1

Moment Arm $\doteq$ 46 feet

T_{cy} = 22 x 46 = 1012 foot-pounds

I_y = 3.32088×10^6 slug-feet^2

t_{on} = 5.58 seconds

Impulse = 22 x 5.58 $\doteq$ 123 pound-seconds

Propellant = 0.45 pounds with an I_{sp} = 270 seconds

UNCONTROLLED ROLL MOTION VS. TIME FOR VARIOUS ORIENTATIONS RELATIVE TO LOCAL VERTICAL

Time (sec)	ψ(deg)	ω(deg/sec x 10^{-3})
0	0.0	0.0
30	0.02	1.34
60	0.08	2.74
90	0.18	4.15
120	0.33	5.60
150	0.52	7.06
180	0.75	8.54
210	1.03	10.03
240	1.36	11.52

Table 1 ($\alpha \doteq 30°$)*

Time (sec)	ψ(deg)	ω(deg/sec x 10^{-3})
0	0.0	0.0
30	0.02	1.44
60	0.09	2.86
90	0.19	4.24
120	0.34	5.59
150	0.53	6.90
180	0.75	8.16
210	1.02	9.37
240	1.32	10.52
270	1.65	11.63

Table 2 ($\alpha \doteq 50°$)*

* α is the angle that the Y axis of the spacecraft makes with the local vertical.

UNCONTROLLED ROLL MOTION VS. TIME FOR VARIOUS ORIENTATIONS RELATIVE TO LOCAL VERTICAL

Time (sec)	ψ(deg)	ω(deg/sec x 10^{-3})
0	0.0	0.0
30	0.01	0.90
60	0.05	1.71
90	0.12	2.44
120	0.20	3.09
150	0.30	3.64
180	0.42	4.11
210	0.55	4.49
240	0.68	4.77
270	0.83	4.96
300	0.98	5.06

Table 3 ($\alpha \simeq 70°$)*

Time (sec)	ψ(deg)	ω(deg/sec x 10^{-3})
0	0.0	0.0
60	0.004	0.20
120	0.03	0.81
180	0.11	1.80
210	0.17	2.45
240	0.26	3.18
270	0.36	4.01
300	0.50	4.92
330	0.66	5.92
360	0.85	7.00
390	1.08	8.15
420	1.34	9.37
450	1.65	10.65

Table 4 ($\alpha \simeq 90°$)*

* α is the angle that the Y axis of the spacecraft makes with the local vertical.

APPENDIX B

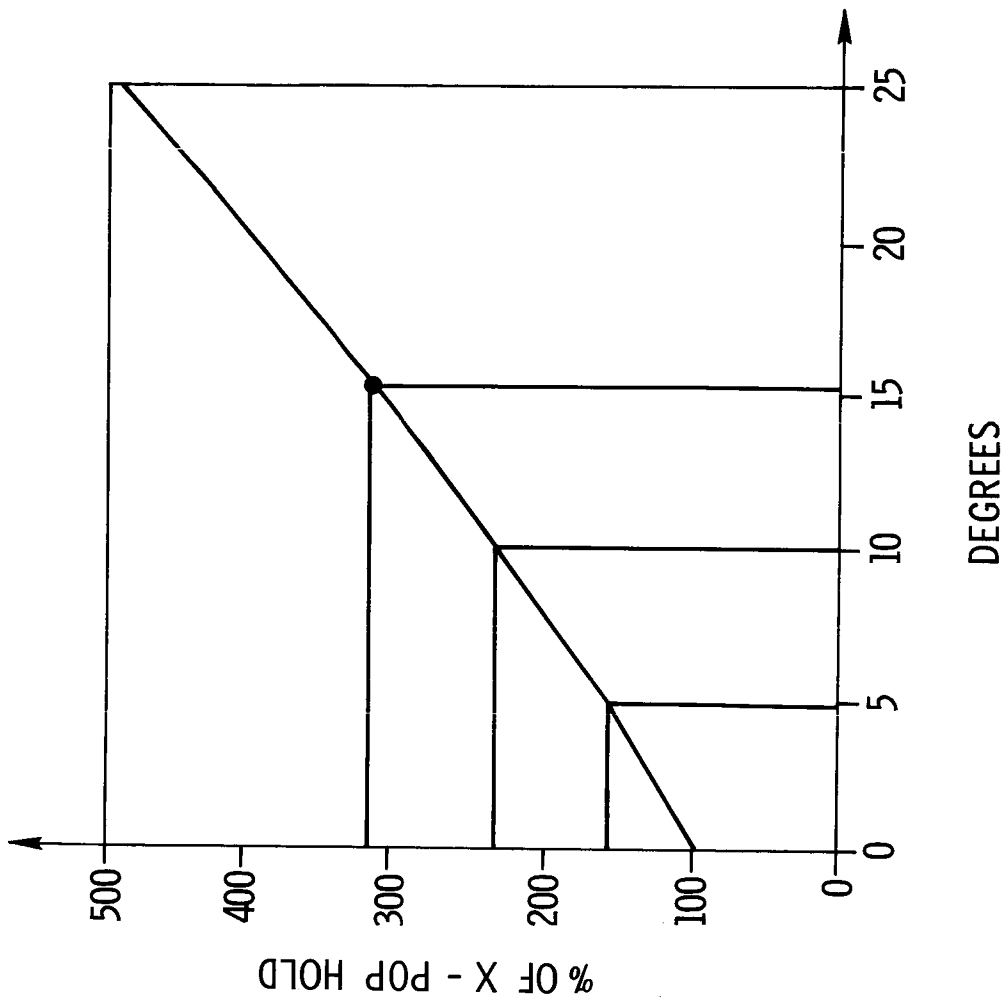

FIGURE 1 IMPULSE PENALTY FOR OFF X - POP HOLD
(PRESENTED AT SECOND WACS REQUIREMENT WORKING GROUP
MEETING AT MSC ON SEPTEMBER 10, 1968)

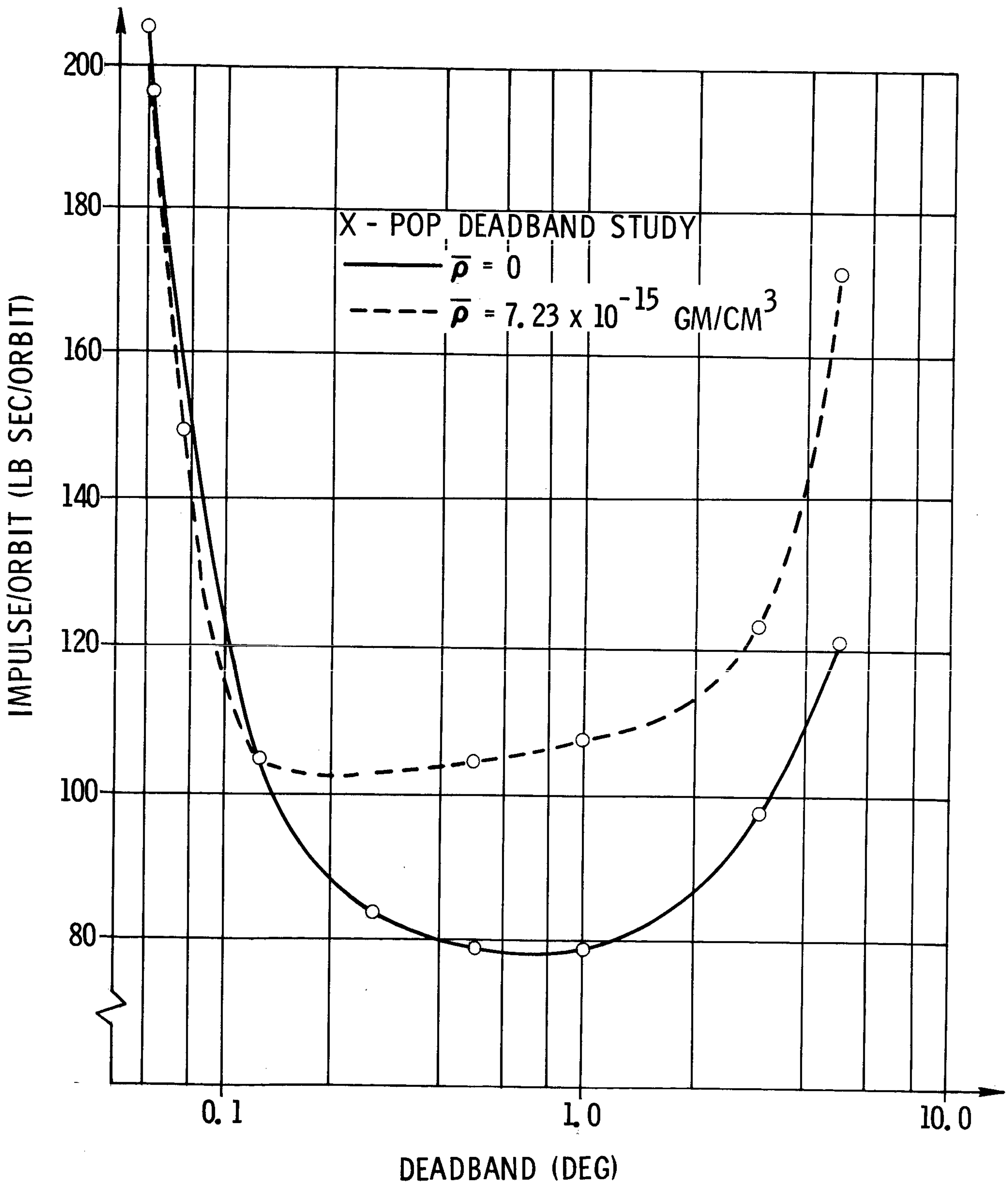
X - POP DEADBAND STUDY
$\bar{\rho}$ = 0
$\bar{\rho}$ = 7.23 x 10^{-15} GM/CM^3
IMPULSE/ORBIT (LB SEC/ORBIT)
200
180
160
140
120
100
80
0.1
1.0
10.0
DEADBAND (DEG)

FIGURE 2

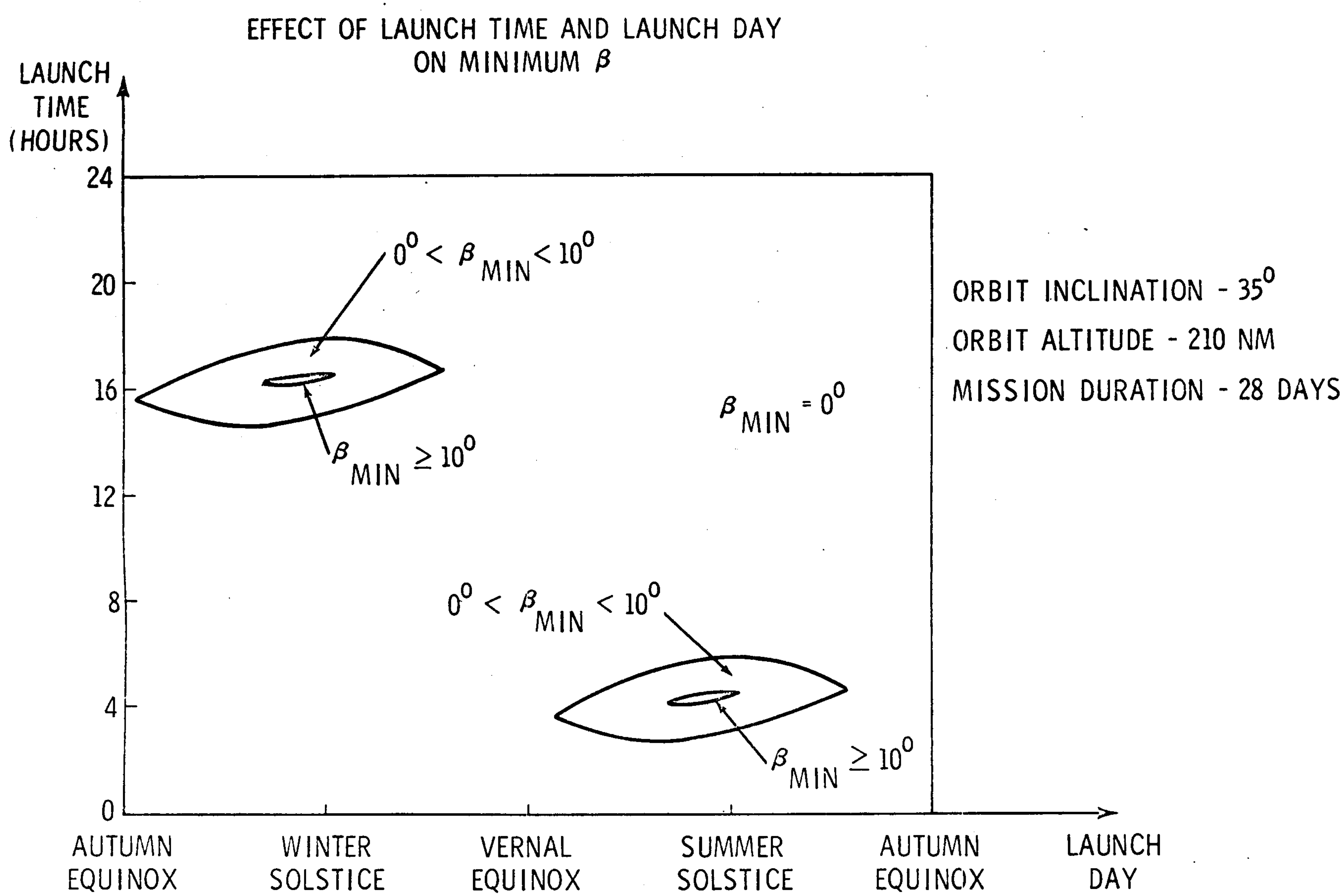

FIGURE 3

This figure was supplied by B. D. Elrod, Bellcomm, Inc.

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Subject: 4B Experiment Pointing Capabilities of the WACS - Case 620

From: J. J. Fearnsides

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